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Multi-level synchrotron radiation-based microtomography of the dental alveolus and its consequences for orthodontics

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ABSTRACT

Multilevel synchrotron radiation-based microtomography has been performed on a human jaw segment obtained at autopsy by cutting increasingly smaller samples from the original segment. The focus of this study lay on the microstructure of the interface between root, periodontal ligament (PDL) and alveolar bone in order to find an answer to the question why alveolar bone remodels during orthodontic loading, when the associated stress and strain levels calculated with finite element analyses are well below the established threshold levels for bone remodeling.

While the inner surface of the alveolus appears to be rather smooth on the lower resolution scans, detailed scans of the root–PDL–bone interface reveal that on a microscopical scale it is actually quite rough and uneven with bony spiculae protruding into the PDL space. Any external (orthodontic) loading applied to the root, when transferred through the PDL to the alveolar bone, will cause stress concentrations in these spiculae, rather than be distributed over a “smooth surface”. As osteocyte lacunae are shown to be present in these spiculae, the local amplified stresses and strain can well be registered by the mechano-sensory network of osteocytes. In addition, a second stress amplification mechanism, due to the very presence of the lacunae themselves, is evidence that stresses and strains calculated with FE analyses, based on macroscopical scale models of teeth and their supporting structures, grossly underestimate the actual mechanical loading of alveolar bone at tissue level. It is therefore hypothesized that remodeling of alveolar bone is subject to the same biological regulatory process as remodeling in other bones.

1. Introduction

Being a former Ph.D-student at Nijmegen University with Rik Huiskes as my supervisor in the late 1980s and early 1990s, I (M.D.) have learned from him to look upon bone as an amazing material. And this amazement did not cease, when I largely traded orthopedic biomechanics for orthodontic biomechanics in the late 1990s. Of all the medical specialties it is orthodontics, which probably has the most direct application of biomechanical principles to achieve the treatment goal. By exerting mechanical loads to the maloccluded teeth through a range of orthodontics appliances, the forces and moments are transferred from brackets or splints on the teeth to the alveolar bone (the bone containing the tooth sockets) supporting the roots, and remodeling processes are initiated here, which then allow the teeth to move gradually to their new position in the jaw. This link between mechanical input and biological output is, however, not straightforward as the teeth and the alveolar bone are connected by a thin, mechanically complex soft tissue, the periodontal ligament (PDL). In the quest for the “Holy Grail” of orthodontics—the optimal force to move teeth—many have set out, yet the present knowledge essentially has not changed over the last two or three decades. In their review article, Ren et al. (2003) have summarized the main findings from the orthodontic literature on this subject over the last five decades and they found values for orthodontic force magnitudes from studies on humans to vary between 18 and 1500 cN, a range covering two orders of magnitude. The authors of the review article did show that in more recent years a definite trend towards smaller orthodontic forces can be identified. And this gives rise to another problem. The stresses and strains in the alveolar bone, calculated with FE-analyses of teeth loaded by orthodontic forces as low as 18 cN (Iwasaki et al., 2000), are by far too low to trigger adaptive bone remodeling processes according to Frost's Mechanostat theory (Frost, 1987), a modern-day interpretation of Wolff's law (Frost, 1998, 2004). For this, strain levels between roughly 800 and 1500 μstrain are required. So, to speak with the words of Rik Huiskes (2000): What are the questions, when the answer would be “*alveolar bone*”? Rik always advocated bone remodeling to be a biological regulatory process, “governed by mechanical usage and orchestrated by osteocyte mechanosensitivity”. Yet, would

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different rules apply to different types of bone? We do know that orthodontic tooth movement is only possible due to alveolar bone remodeling and so we come to a similar question raised by Melsen (2001): "Can osteocytes distinguish between orthopedists and orthodontists and behave differently to their treatment regimes, or are osteocytes in the dental alveolus basically the same as the ones in a long bone and get triggered to initiate bone remodeling at the same mechanical threshold signals?" In case of the latter, the proper insight into the mechanics of the root–PDL–bone interface is still incomplete and the alveolar load transfer is poorly understood. We know that the root–PDL–bone interface is important for a correct understanding of the load transfer of masticatory forces and orthodontic loads from the teeth via the periodontal ligament and the alveolar bone to the rest of the jaw. Although many experimental studies have demonstrated the non-linear behavior of the PDL (Komatsu et al., 1998; van Driel et al., 2000; Yoshida et al., 2001; Dorow et al., 2003; Kawarizadeh et al., 2003; Sanctuary et al., 2005; Jónsdóttir et al., 2006; Papadopoulou et al., 2013), it is still often inherently (and erroneously) assumed to be linear-elastic when referring to the so-called "compression-tension" theory to describe the load transfer of orthodontic load to the alveolar bone. FE-analyses, where this non-linear behavior of the PDL was incorporated have shown an entirely different load transfer pattern than would be expected from the "compression-tension" theory (Toms and Eberhardt, 2003; Cattaneo et al., 2005; Bourauel et al., 2007; Cattaneo et al., 2009). In addition, attention has been drawn previously to the way the lamina dura (the actual tooth socket consisting of a thin layer of cortical bone) of the alveolar bone is connected and supported by the rest of the bone in the jaw (Dalstra et al., 2006a, 2006b). Only cervically (where the tooth enters its socket) it is well merged into the cortical bone on the outside of the jaw, but going apically (at the tip of the root) the lamina dura receives gradually less support as it is only connected to porous trabecular bone. Moreover, this inhomogeneous support also depends on the anatomical directions. This has consequences for the exact location of the so-called center of resistance of

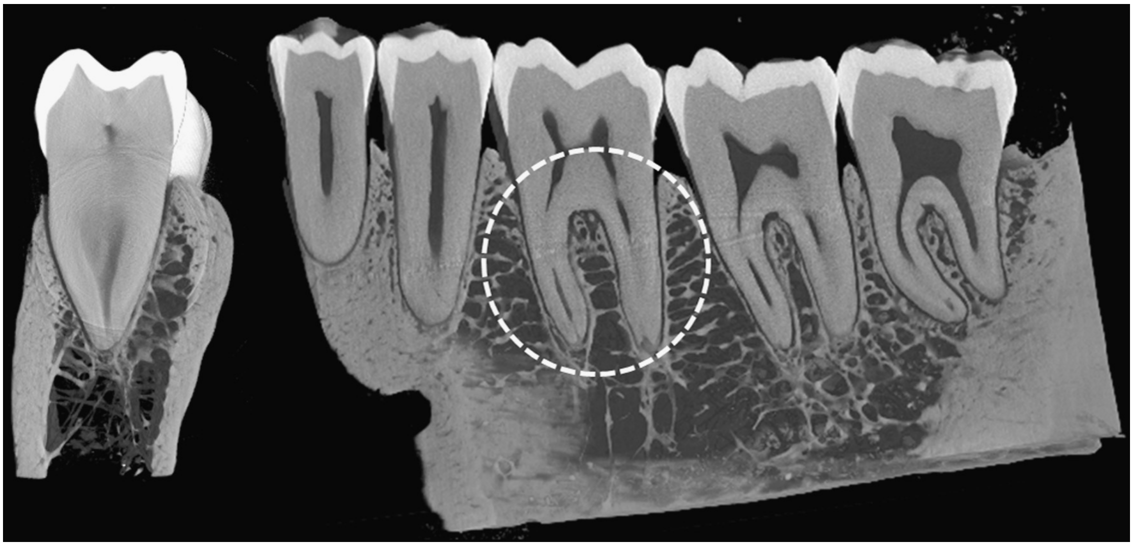

Fig. 1. 3D reconstruction of a bucco-lingual (left) and mesio-distal cross-section through the entire segment (right). In the latter, the approximate position of the 10 mm core drill sub-sample is shown. Note the lamina dura of the alveolar bone as a thin layer of bone surrounding the roots. The dark "empty" space between the root and the lamina dura is occupied by the PDL.

Fig. 2. 3D reconstruction of the coronal (left) and lateral view (right) of the 10 mm cylindrical sub-sample of the root of the first molar. Note the drill holes, where the six 1.5 mm cylindrical sub-samples have been harvested. In the lateral view it can be seen that the root on the left side is supported by trabecular bone, whereas the root on the right is supported by cortical bone.